



中国科学院大学
University of Chinese Academy of Sciences



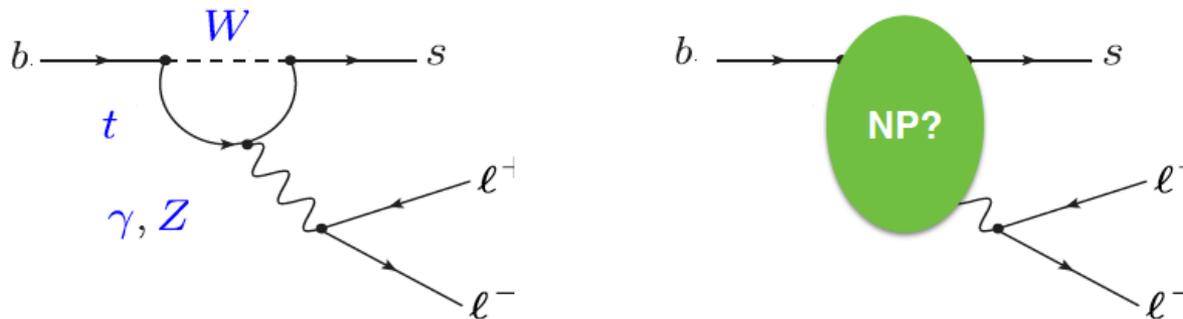
Rare decays at LHCb

Jibo HE/何吉波(UCAS), for the LHCb collaboration

Presented at HFCPV2017 @ CCNU

Introduction

- Flavor-Changing Neutral Current (FCNC) process suppressed in SM. New Physics?



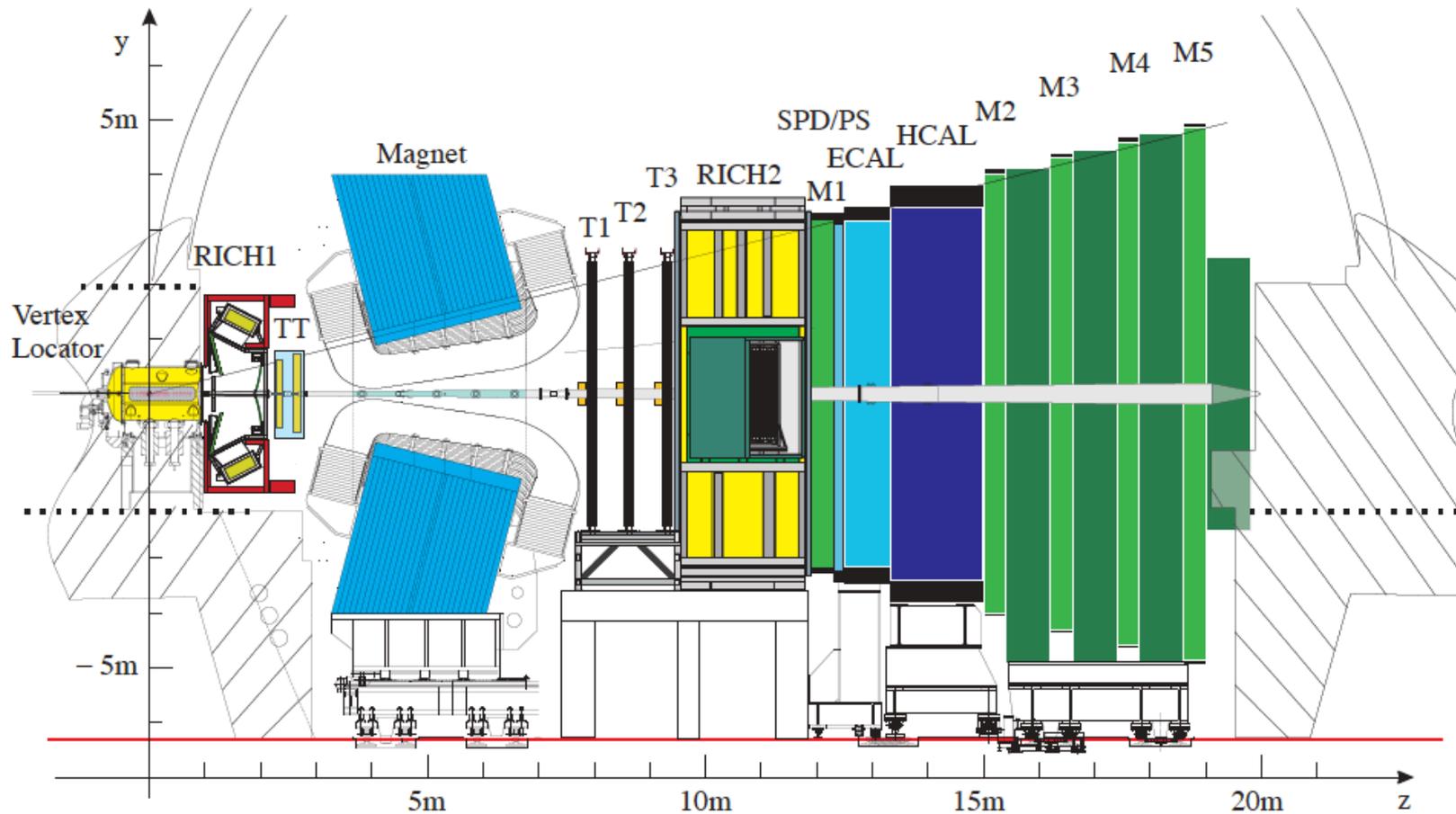
- Described by effective Hamiltonian

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [C_i(\mu) \mathcal{O}_i(\mu) + C'_i(\mu) \mathcal{O}'_i(\mu)]$$

$\underbrace{\hspace{10em}}$ left handed	$\underbrace{\hspace{10em}}$ right handed (suppressed in the SM)	i=1, 2 i=3-6, 8 i=7 i=9, 10 i=S i=P	Tree Gluon penguin Photon penguin Electroweak penguin Higgs (scalar) penguin Pseudoscalar penguin
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The LHCb experiment

- Dedicated to **precision study** of b/c -hadrons

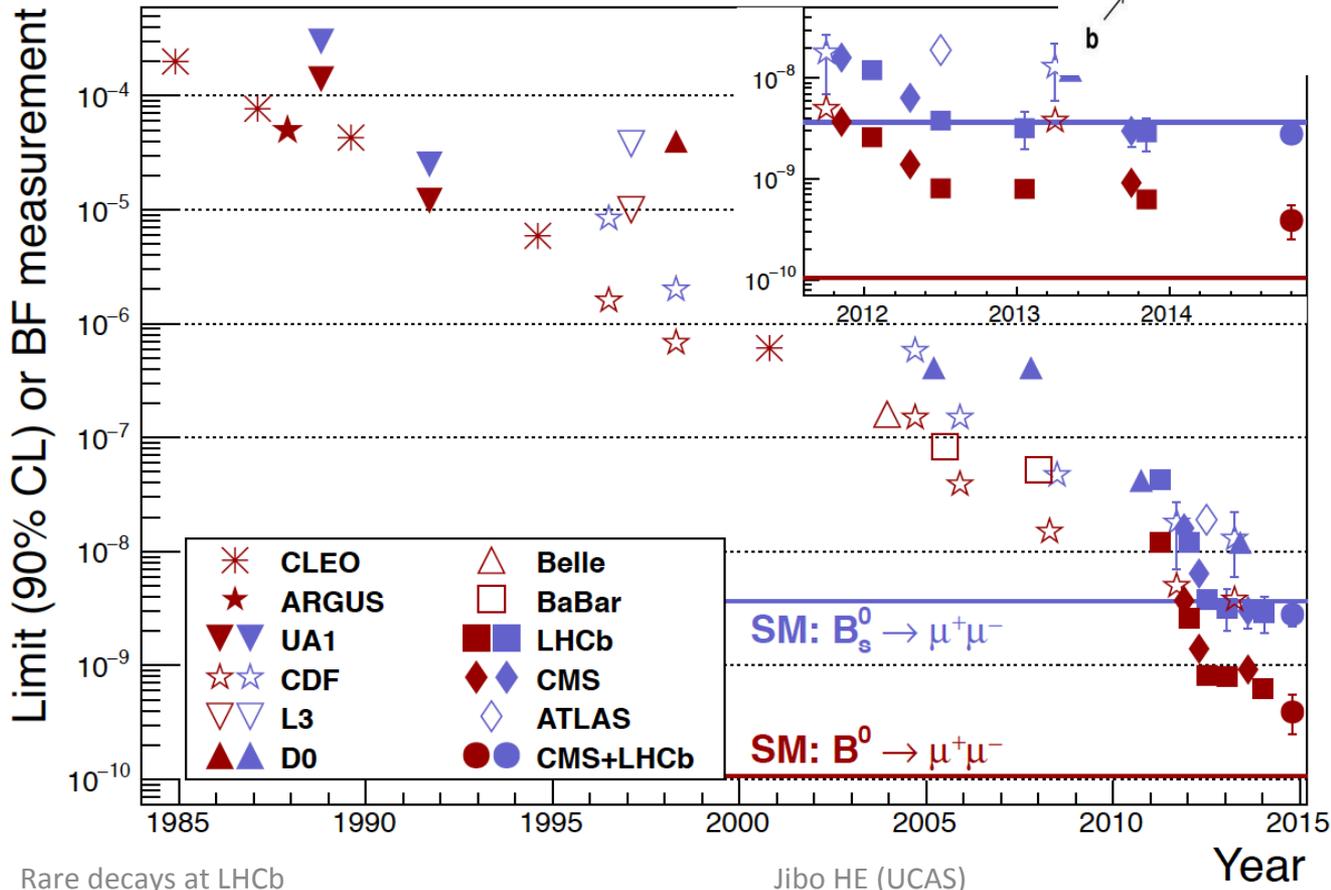
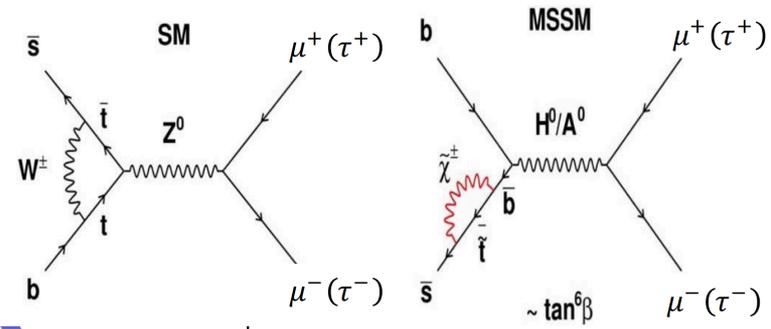


Rare decays at LHCb

- Very rare decays
 - $B_{(s)} \rightarrow \mu^+ \mu^-$, $B_{(s)} \rightarrow \tau^+ \tau^-$, $B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
- Lepton flavor violation
 - $B_{(s)} \rightarrow e^+ \mu^-$, $\tau^+ \rightarrow \mu^+ \mu^- \mu^+$
- Electroweak penguin
 - $B \rightarrow K^{(*)} \mu^+ \mu^-$, $\Lambda_b \rightarrow \mu^+ \mu^- p K^- (\pi)$, LFU (see G. Wormser's talk)
- Radiative
 - $B_s \rightarrow \phi \gamma$, $B \rightarrow K \pi \pi \gamma$
- Rare charm, covered by L. Sun
- Rare Strange
 - $K_S \rightarrow \mu^+ \mu^-$

$B_{(s)} \rightarrow \mu^+ \mu^-$

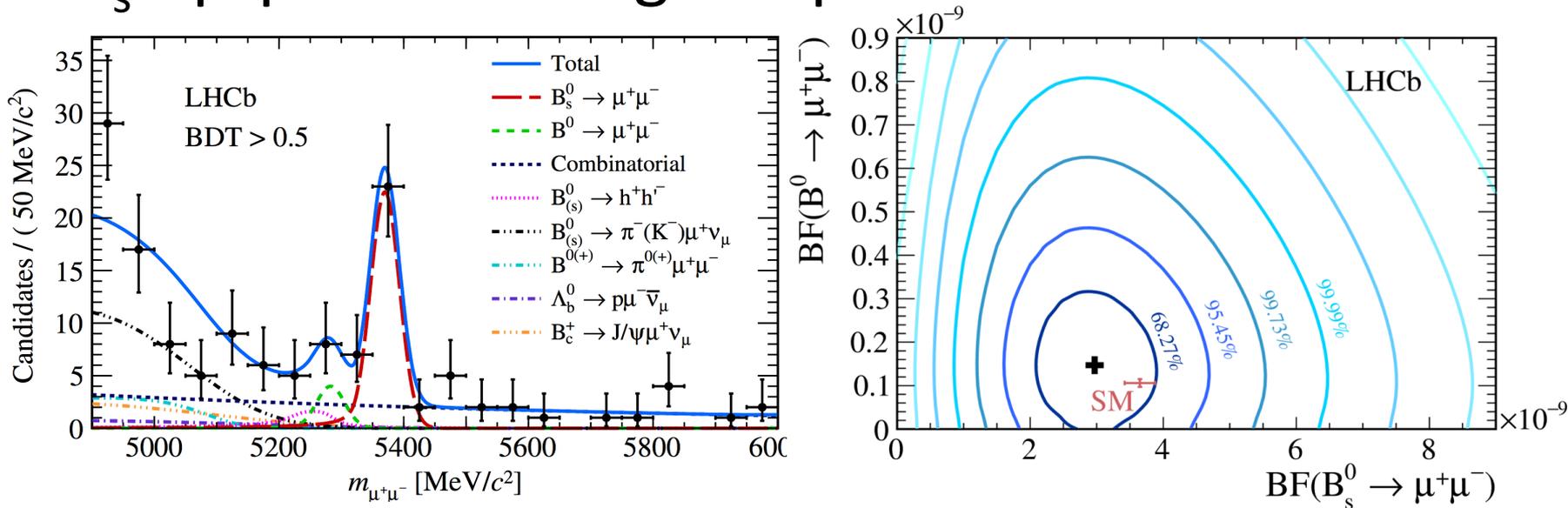
- Road to $B_{(s)} \rightarrow l^+ l^- \dots$



$B_{(s)} \rightarrow \mu^+ \mu^-$, latest results from LHCb

- With 4.6 fb^{-1} of data, first observation of $B_s \rightarrow \mu^+ \mu^-$ from a single experiment

[PRL 118 (2017) 191801]



$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad 7.8\sigma \text{ LHCb alone}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \cdot 10^{-10} \quad @ 95\% \text{ CL}$$

$B_s \rightarrow \mu^+ \mu^-$ effective lifetime

- B_s mixing => effective τ

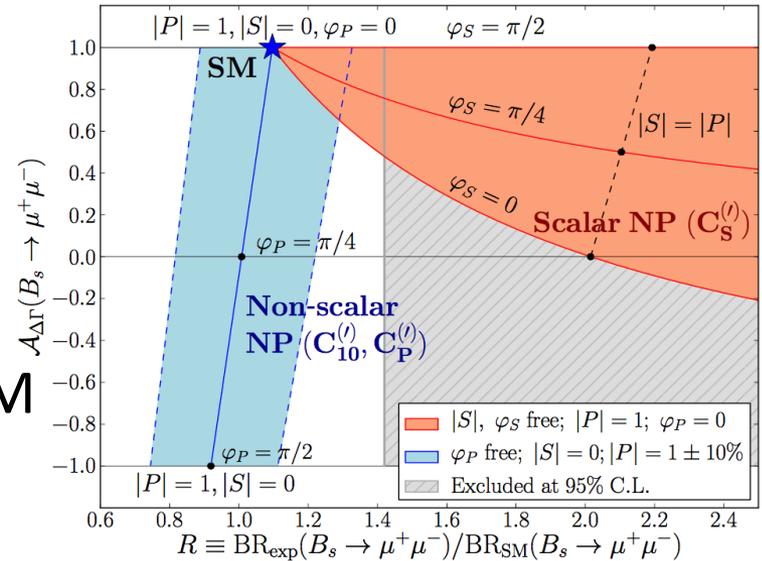
$$\tau_{\mu\mu} = \frac{\tau_{B_s}}{(1 - y_s^2)} \frac{1 + 2y_s A_{\Delta\Gamma} + y_s^2}{1 + y_s A_{\Delta\Gamma}}$$

$$A_{\Delta\Gamma}^f = \frac{\Gamma(B_{s,H} \rightarrow f) - \Gamma(B_{s,L} \rightarrow f)}{\Gamma(B_{s,H} \rightarrow f) + \Gamma(B_{s,L} \rightarrow f)} \quad A_{\Delta\Gamma} = 1 \text{ in SM}$$

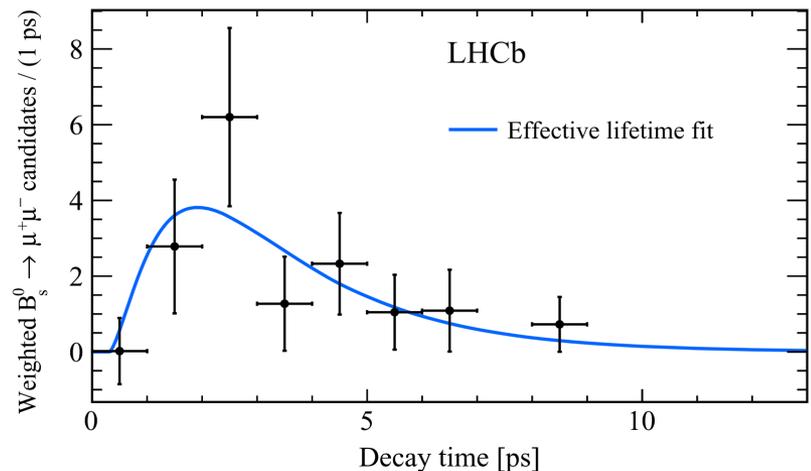
$$y_s \equiv \tau_{B_s} \Delta\Gamma_s / 2$$

- First measurement, not yet sensitive to $A_{\Delta\Gamma}$

$$\tau(B_s^0 \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$



[De Bruyn *et al.*, PRL 109 (2012) 041801]



$B_{(s)} \rightarrow \tau^+ \tau^-$

- $B_{(s)} \rightarrow \tau^+ \tau^-$ not helicity suppressed in SM, predicted BR ~ 200 higher than $B_{(s)} \rightarrow \mu^+ \mu^-$

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-)_{SM} = (7.73 \pm 0.49) \times 10^{-7}$$

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-)_{SM} = (2.22 \pm 0.19) \times 10^{-8}$$

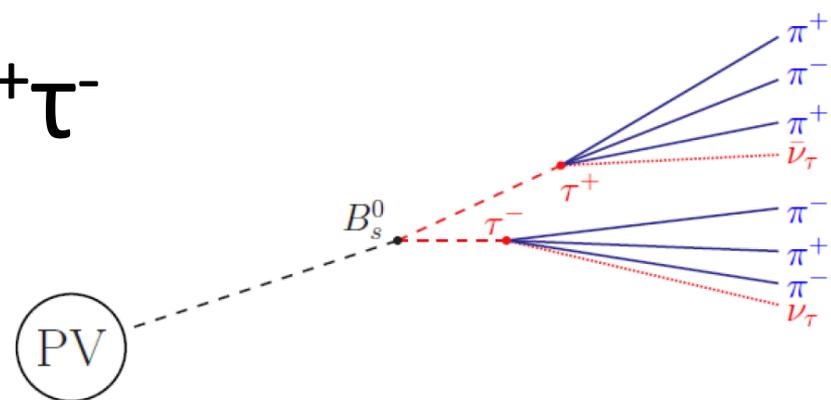
- BR($B_s \rightarrow \tau^+ \tau^-$) enhanced by NP scenarios, previously best limit given by Babar

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 4.1 \times 10^{-3} \text{ @ 90\% C.L.}$$

[Babar, PRL 96 (2006) 241802]

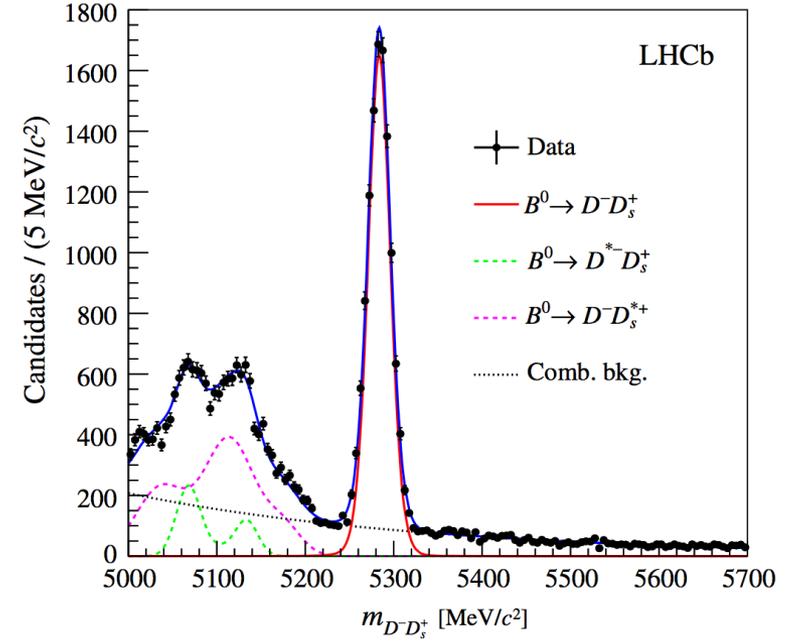
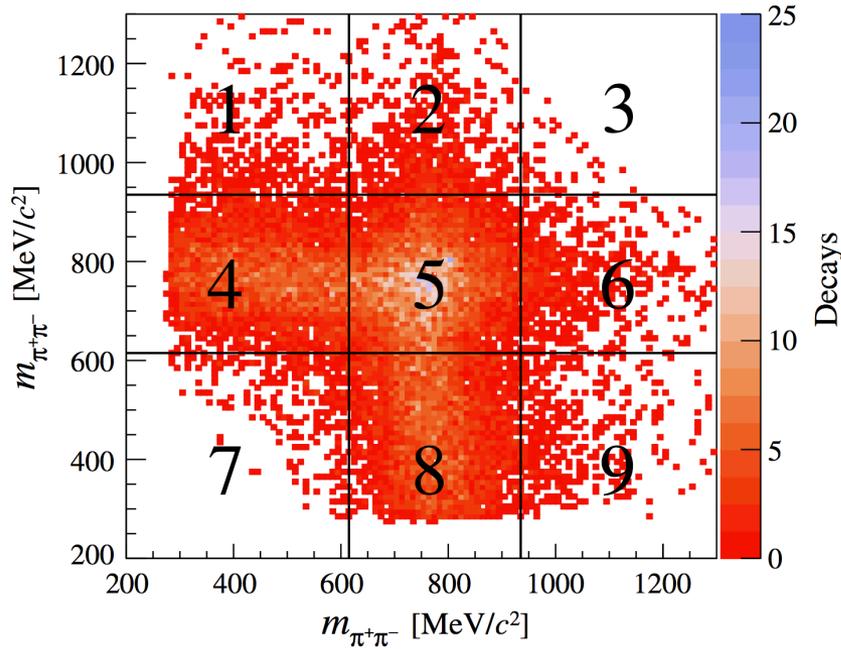
$B_{(s)} \rightarrow \tau^+ \tau^-$

- Using $\tau \rightarrow 3\pi\nu$ (a_1) mode
- Normalized to $B \rightarrow D^+ D_s^-$



[PRL 118 (2017) 251802]

LHCb simulation

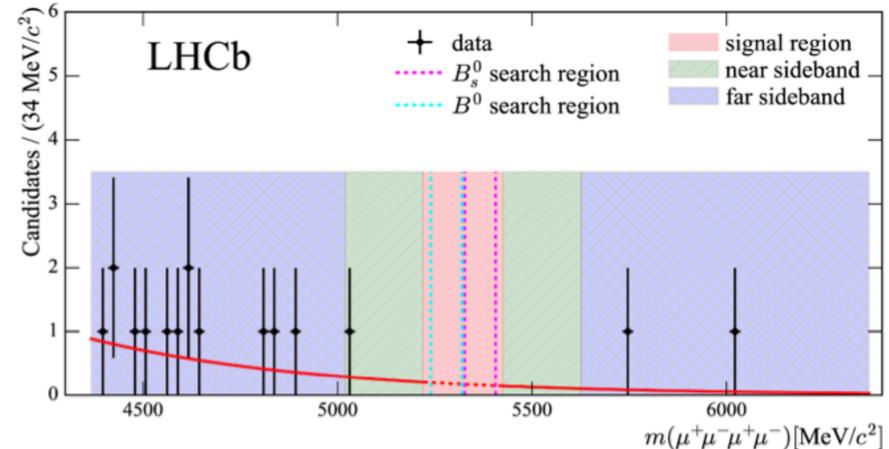
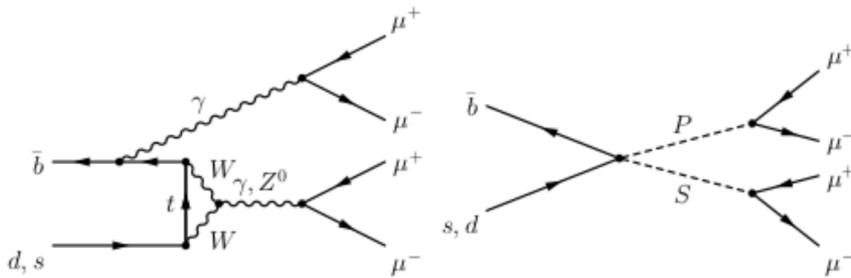


$B(B_s^0 \rightarrow \tau^+ \tau^-) < 5.2(6.8) \times 10^{-3}$ @ 90 (95)% C.L.
 $B(B^0 \rightarrow \tau^+ \tau^-) < 1.6(2.1) \times 10^{-3}$ @ 90 (95)% C.L.

$B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

- Non-resonant $\text{BR}(B_s \rightarrow 4\mu) \sim 3.5 \times 10^{-11}$, can be enhanced in, e.g., MSSM (P, S sgoldstino)

[JHEP 03 (2017) 001]



- Upper limits @95% CL:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 2.5 \times 10^{-9},$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 6.9 \times 10^{-10},$$

$$\mathcal{B}(B_s^0 \rightarrow S(\rightarrow \mu^+ \mu^-)P(\rightarrow \mu^+ \mu^-)) < 2.2 \times 10^{-9},$$

$$\mathcal{B}(B^0 \rightarrow S(\rightarrow \mu^+ \mu^-)P(\rightarrow \mu^+ \mu^-)) < 6.0 \times 10^{-10}.$$

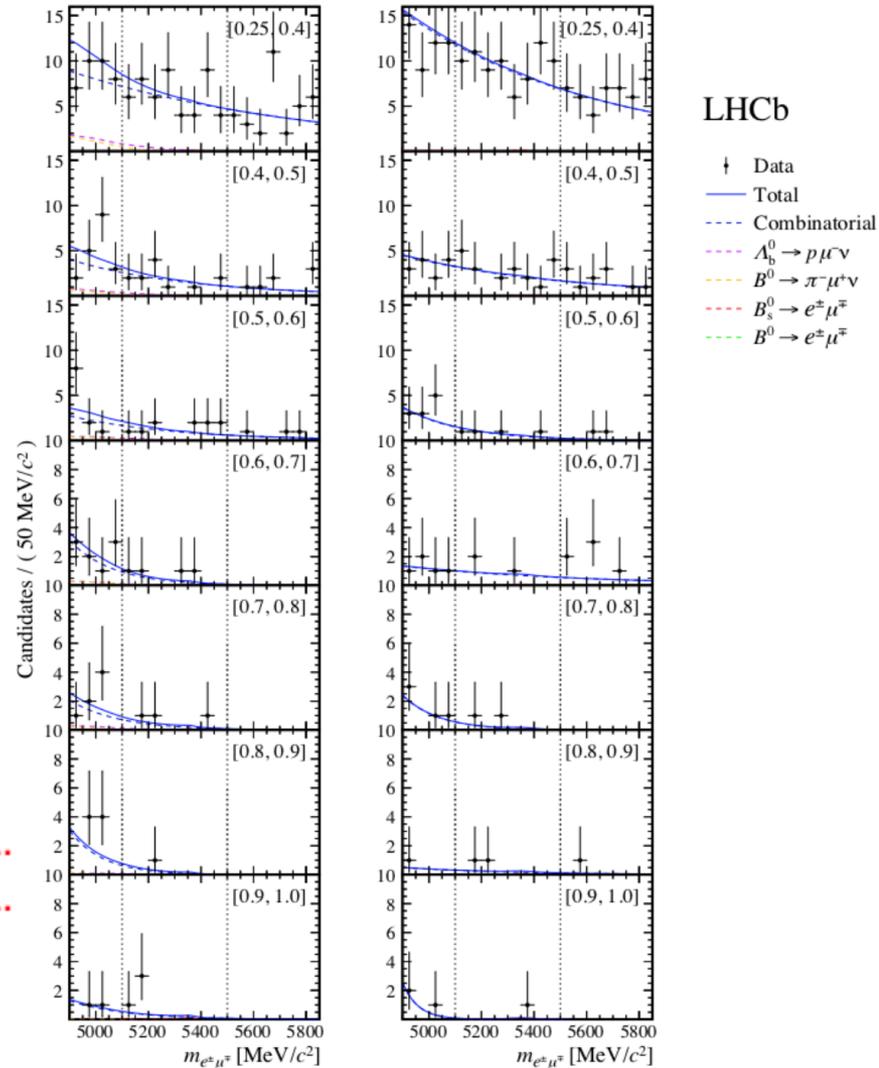
$B_{(s)} \rightarrow e^+ \mu^-$

- LFV forbidden in SM. Observation of LFV? clear sign of NP!
- Normalized to $B^0 \rightarrow K^+ \pi^-$, and $B^+ \rightarrow J/\psi K^+$
- Best upper limits so far:

[arXiv:1710.04111]

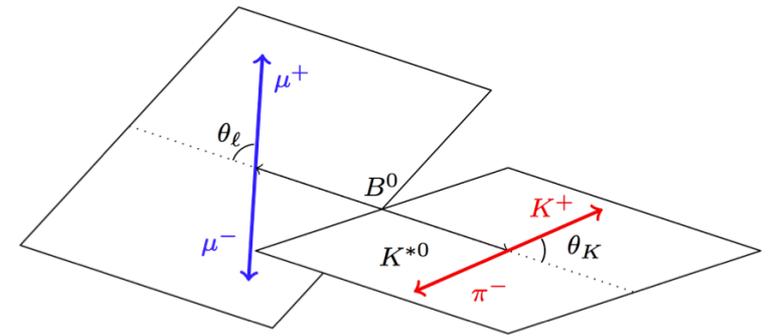
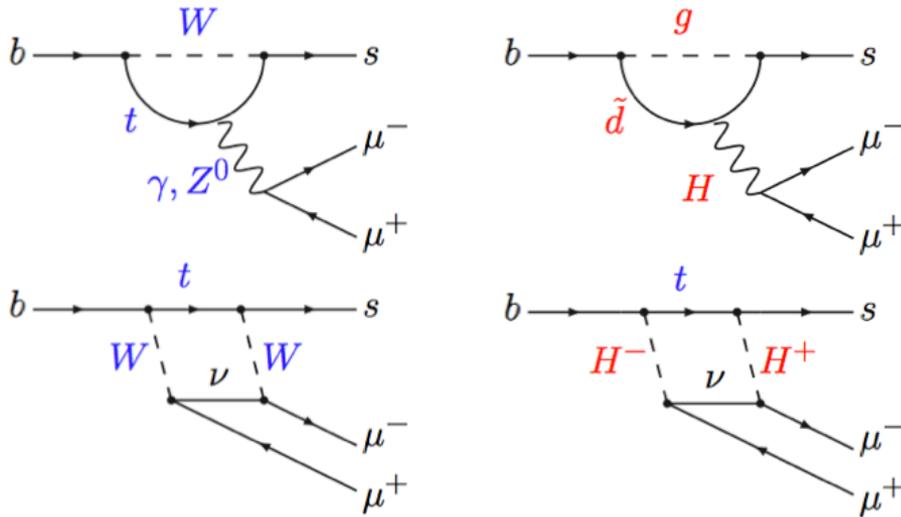
$$\mathcal{B}(B_s^0 \rightarrow e^+ \mu^-) < 5.4(6.3) \times 10^{-9} \text{ @ 90 (95)\% C.L.}$$

$$\mathcal{B}(B^0 \rightarrow e^+ \mu^-) < 1.0(1.3) \times 10^{-9} \text{ @ 90 (95)\% C.L.}$$



$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

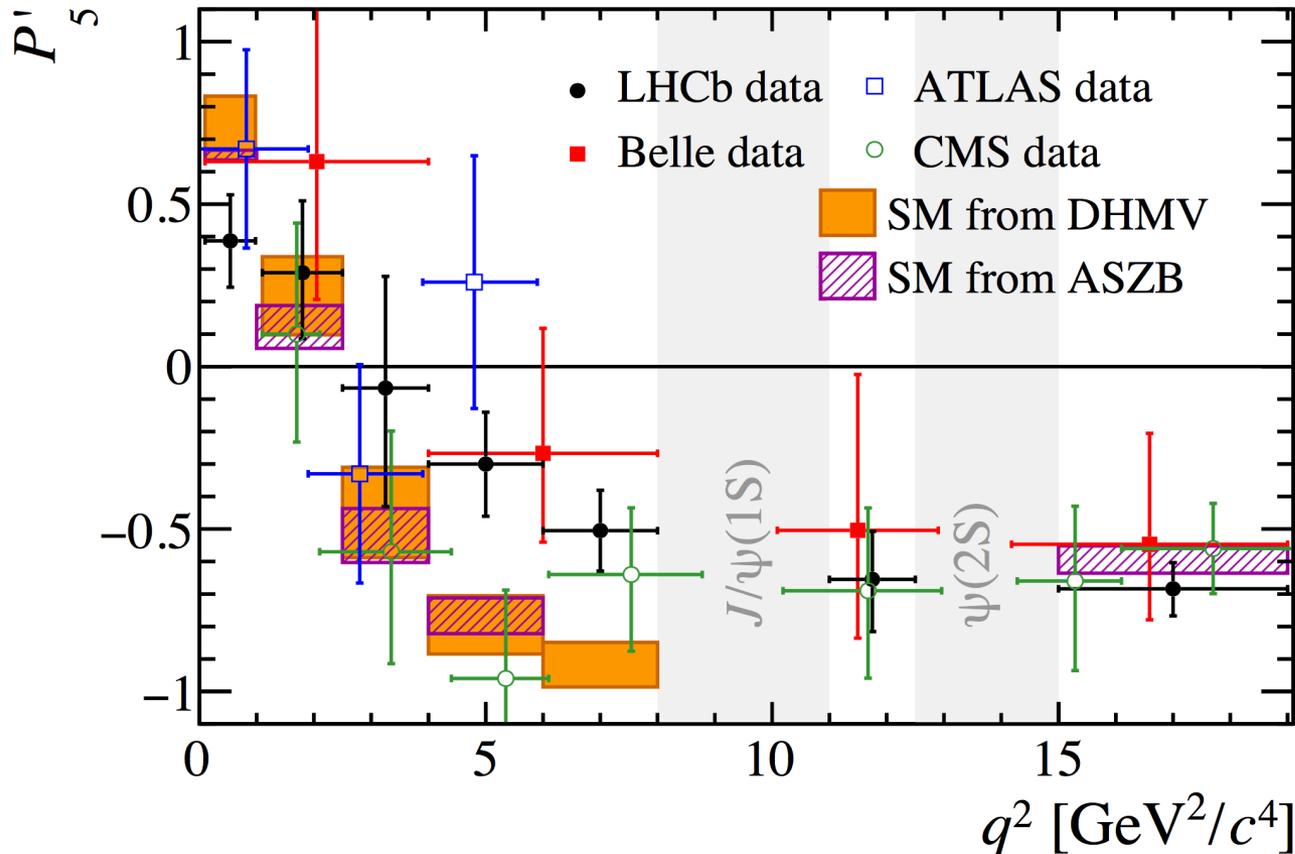
- Rates and angular distributions sensitive to NP



$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ \left. - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \right. \\ \left. + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \right. \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

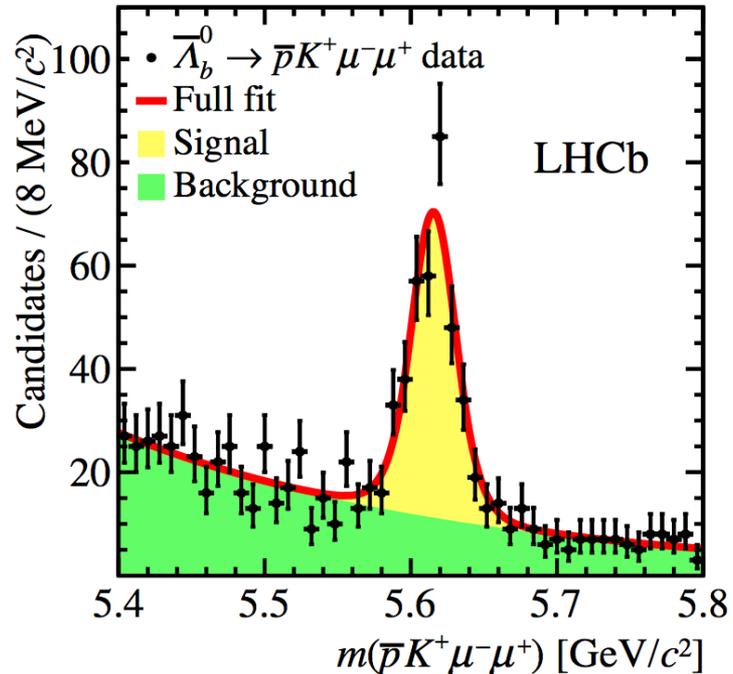
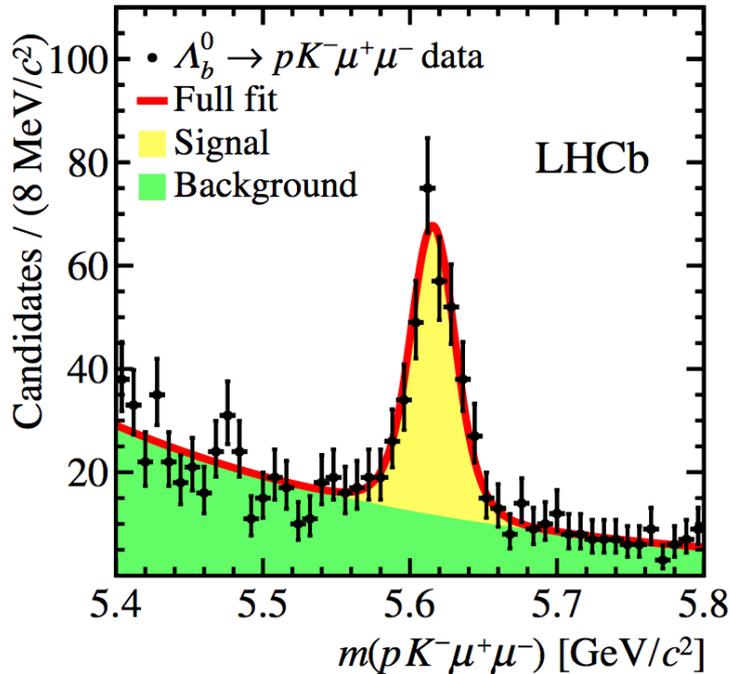
$B^0 \rightarrow K^{*0} \mu^+ \mu^-: P_5'$

- LHCb updated with 3 fb⁻¹, anomaly still there
- Also measured by Belle, ATLAS, CMS



[LHCb, JHEP 02 (2016) 104]
 [Belle, PRL 118 (2017) 111801]
 [ATLAS-CONF-2017-023]
 [CMS, arXiv:1710.02846]

Observation of $\Lambda_b^- \rightarrow pK^- \mu^+ \mu^-$



- Also measured CP asymmetry

$$\Delta \mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(\Lambda_b^0 \rightarrow pK^- \mu^+ \mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \rightarrow pK^- J/\psi)$$

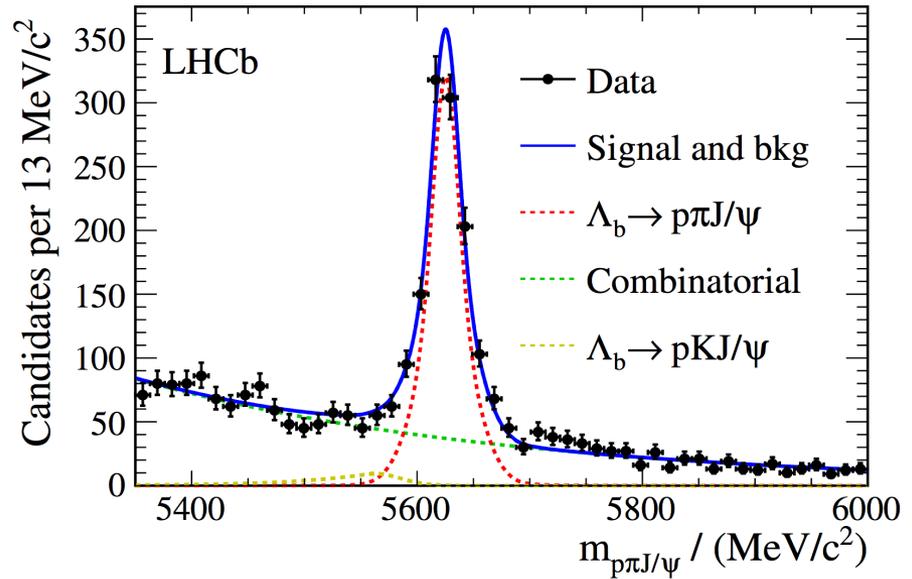
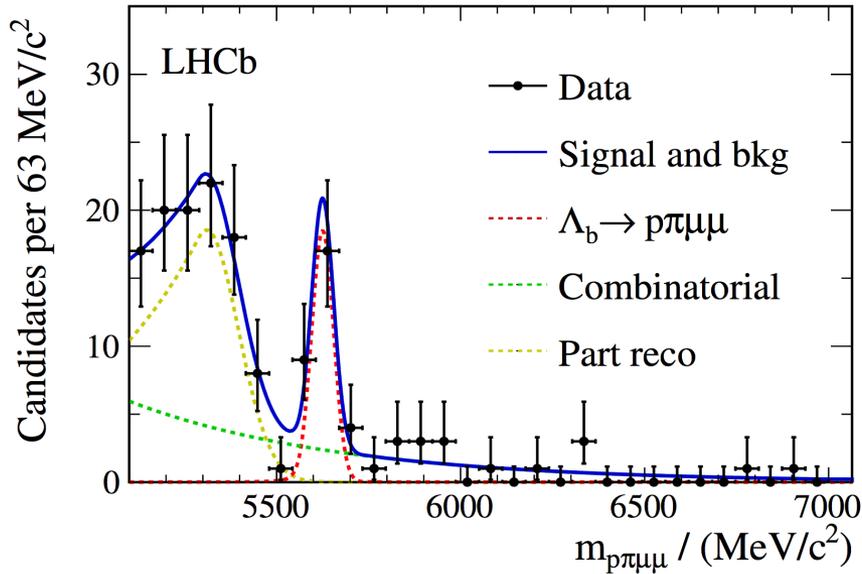
$$\Delta \mathcal{A}_{CP} = (-3.5 \pm 5.0 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-2}$$

$$a_{CP}^{\hat{T}\text{-odd}} = (1.2 \pm 5.0 \text{ (stat)} \pm 0.7 \text{ (syst)}) \times 10^{-2}$$

Observation of $\Lambda_b \rightarrow p\pi\mu^+\mu^-$

- Measured BR w.r.t. $\Lambda_b \rightarrow p\pi J/\psi(\mu^+\mu^-)$

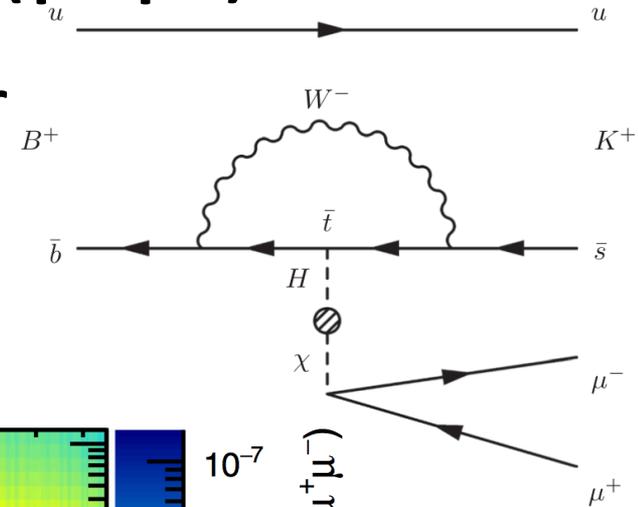
[JHEP 04 (2017) 029]



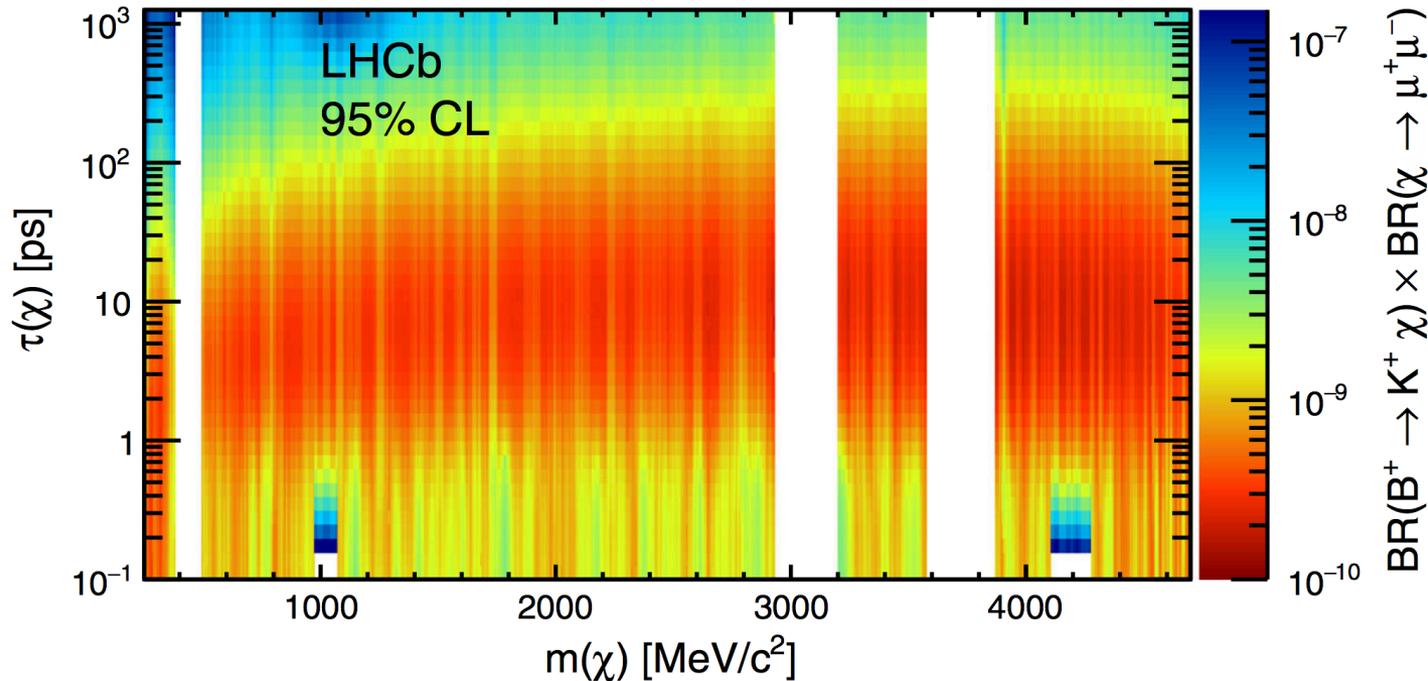
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\pi^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) p\pi^-)} = 0.044 \pm 0.012 \pm 0.007$$

Search for $B \rightarrow K^+ \chi (\mu^+ \mu^-)$

- Search for the long-lived scalar particle χ in the hidden sector



[PRD 95 (2017) 071101(R)]



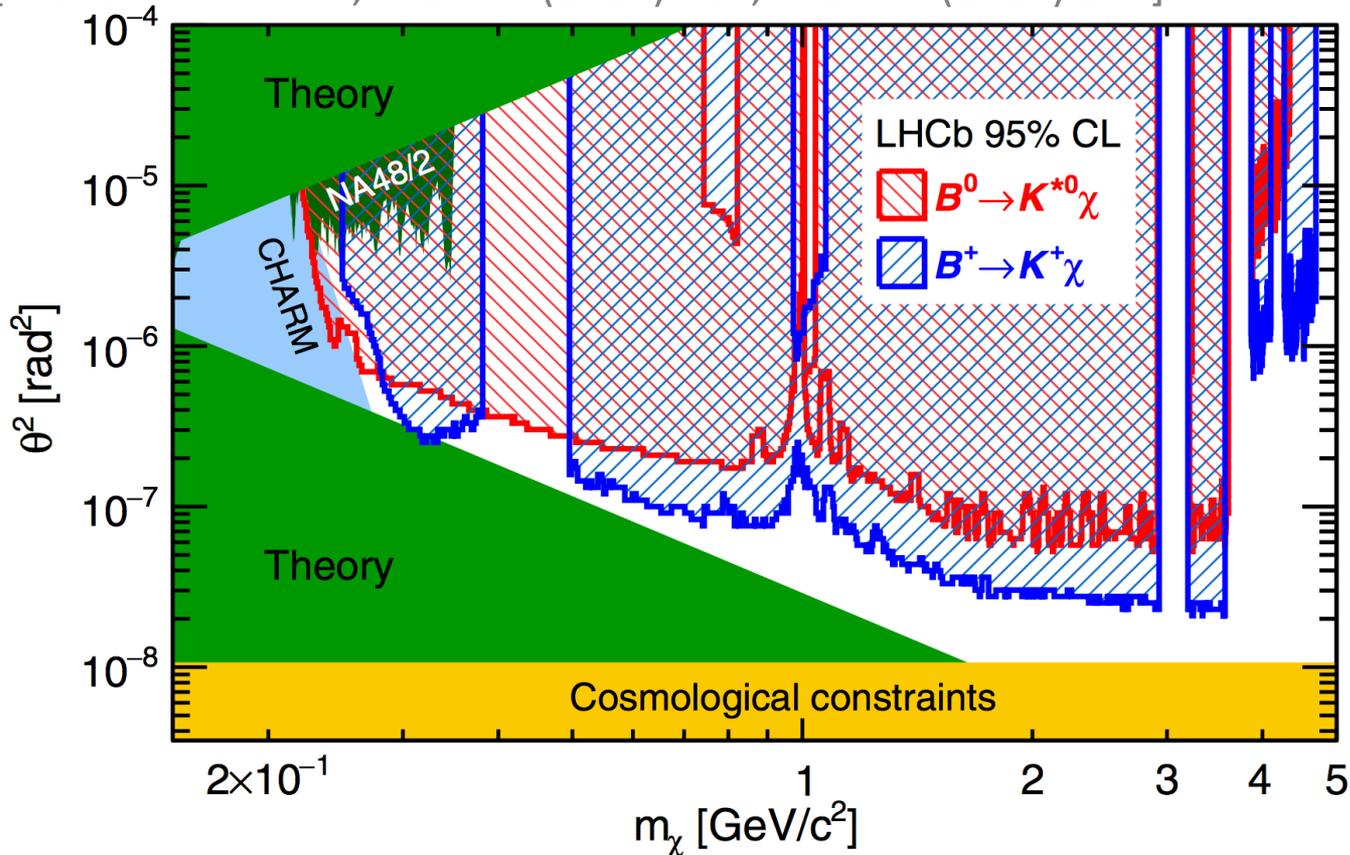
Search for $B \rightarrow K^+ \chi (\mu^+ \mu^-)$ (cont.)

- Parameter space of the inflation model

[B. Batell, *et. al.*, PRD 83 (2011) 054005]

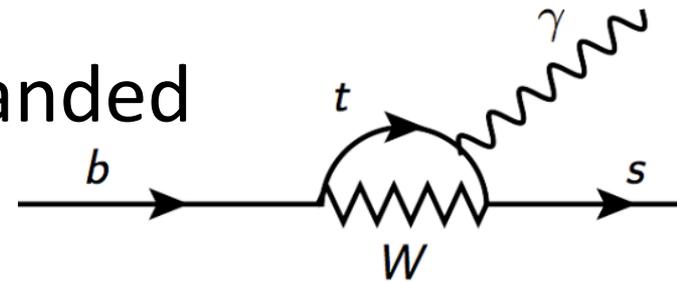
[F. Bezrukov *et. al.*, JHEP 05 (2010) 010, JHEP 07 (2013) 140]

[PRD 95 (2017) 071101(R)]



Photon polarization in $B_s \rightarrow \phi \gamma$

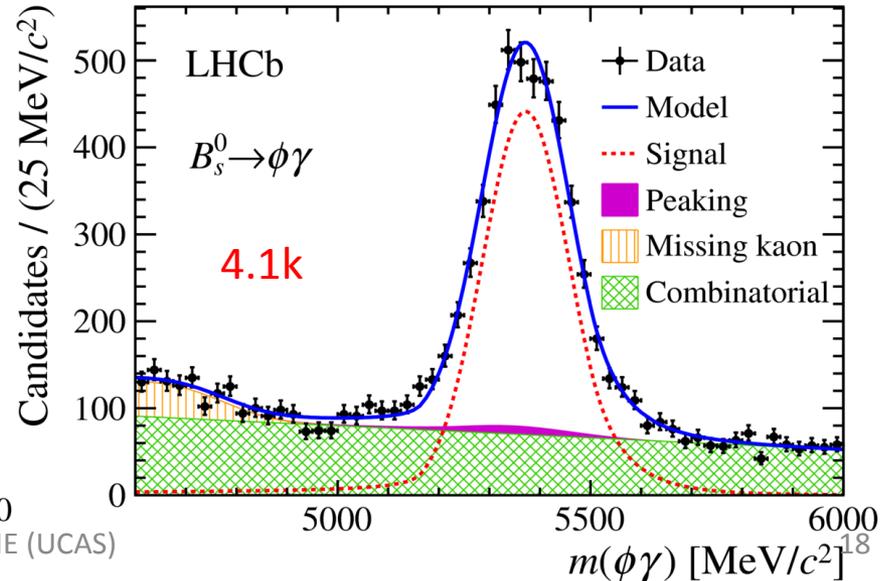
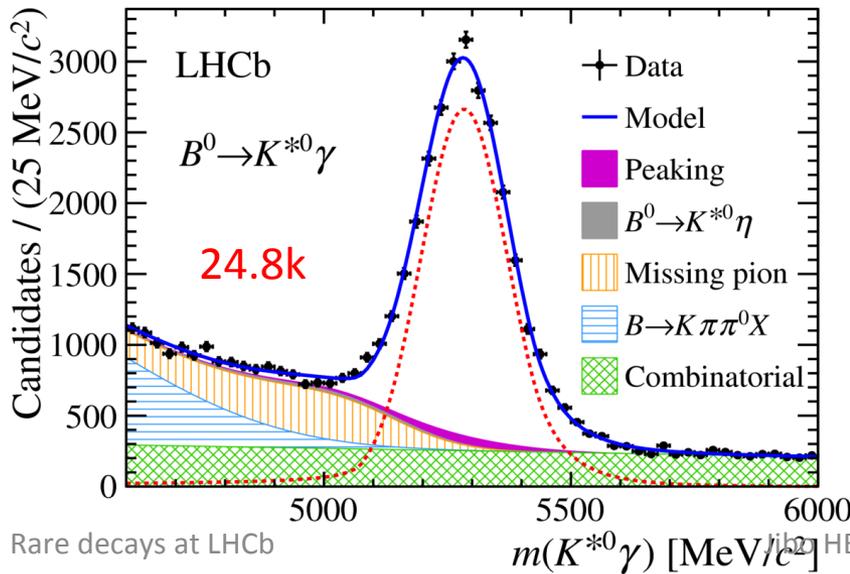
- Photons in $b \rightarrow s \gamma$ mainly left-handed
- Time-dependent signal rate



$$\mathcal{P}(t) \propto e^{-\Gamma_s t} \left\{ \cosh(\Delta\Gamma_s t/2) - \mathcal{A}^\Delta \sinh(\Delta\Gamma_s t/2) \right\}$$

with $\mathcal{A}^\Delta \propto 2 \frac{\gamma_R}{\gamma_L}$. $\mathcal{A}_{SM}^\Delta = 0.05 \pm 0.03$

[PRL 118 (2017) 021801]

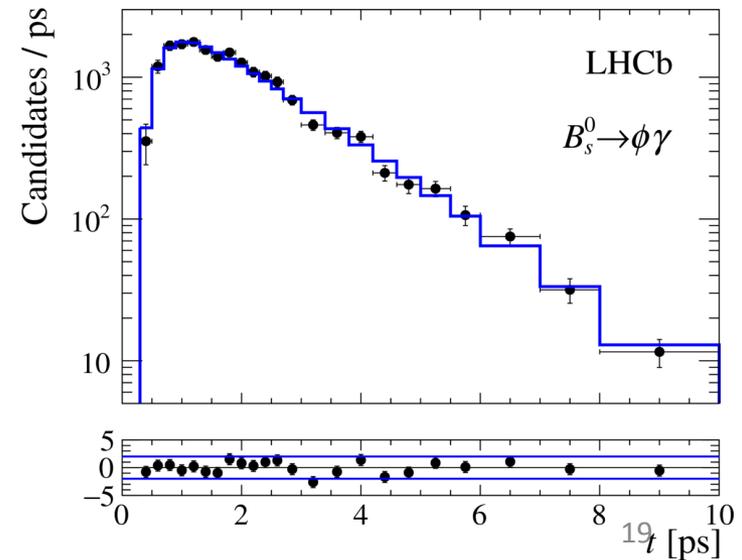
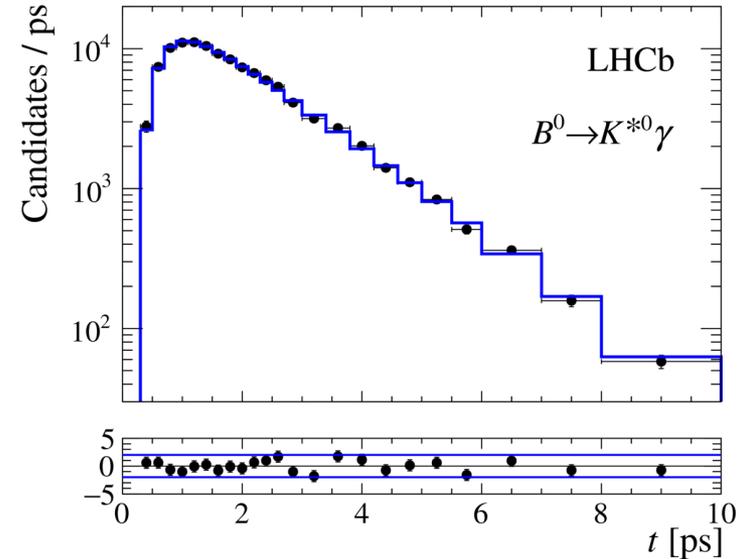
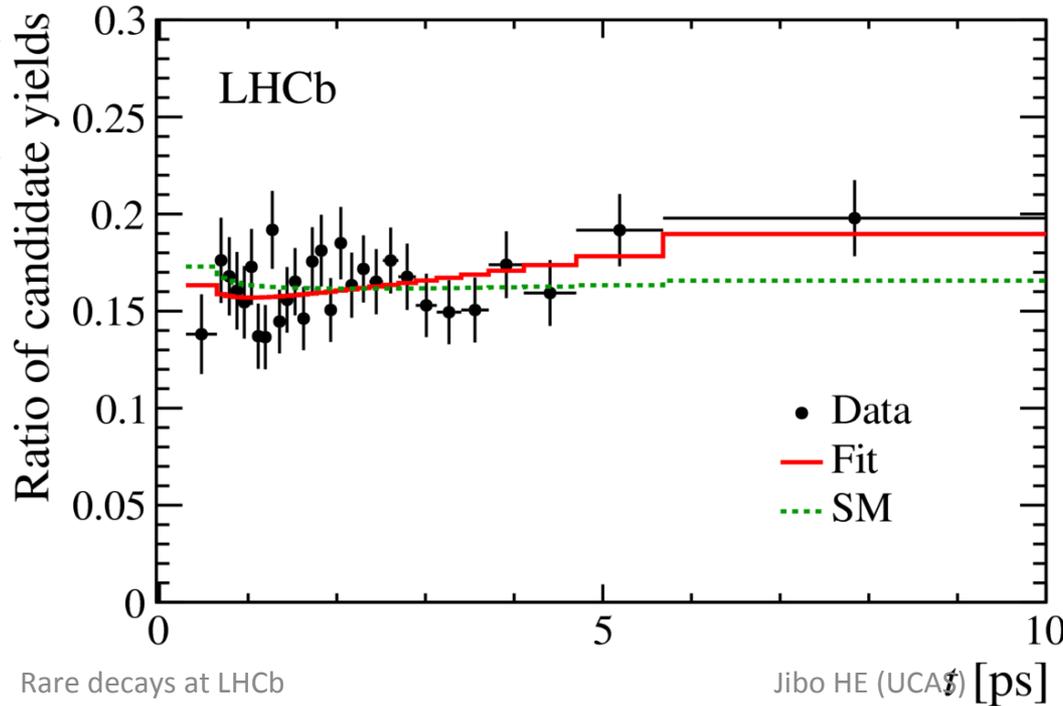


Photon polarization in $B_s \rightarrow \phi \gamma$

- Ratio between B^0/B_s as t
- Compatible with SM in 2σ

$$\mathcal{A}^\Delta = -0.98^{+0.46+0.23}_{-0.52-0.20}$$

[PRL 118 (2017) 021801]

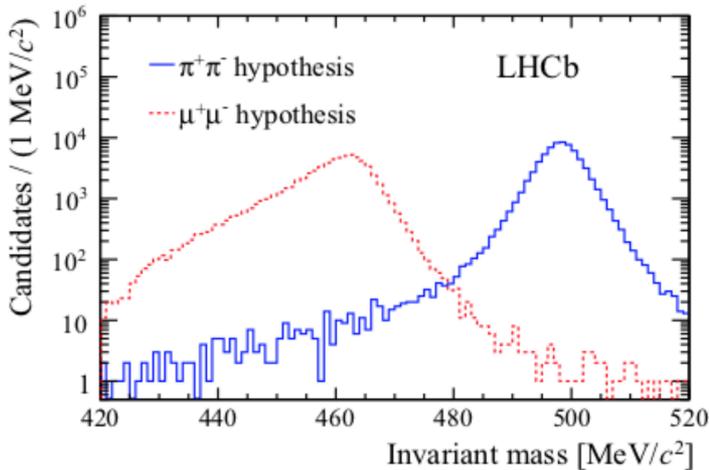


$K_S \rightarrow \mu^+ \mu^-$

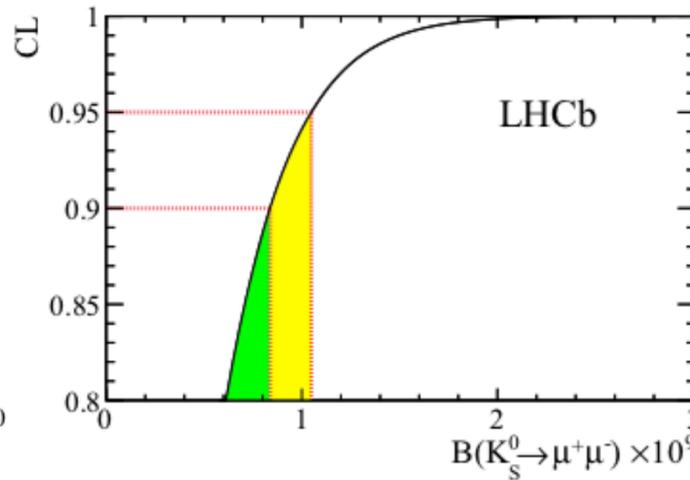
- SM prediction: $BR = (5.0 \pm 1.5) \times 10^{-12}$, can be enhanced up to factor 100
- $K_S \rightarrow \pi^+ \pi^-$: control channel, main Bkg

$$B(K_S^0 \rightarrow \mu^+ \mu^-) < 0.8(1.0) \times 10^{-9} \text{ @ 90 (95)\% C.L.}$$

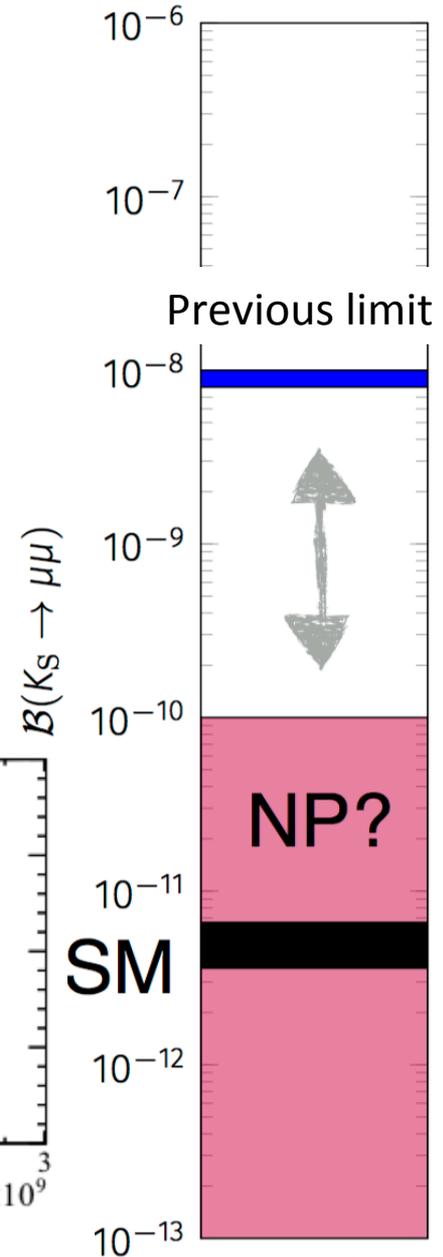
[EPJC 77 (2017) 678]



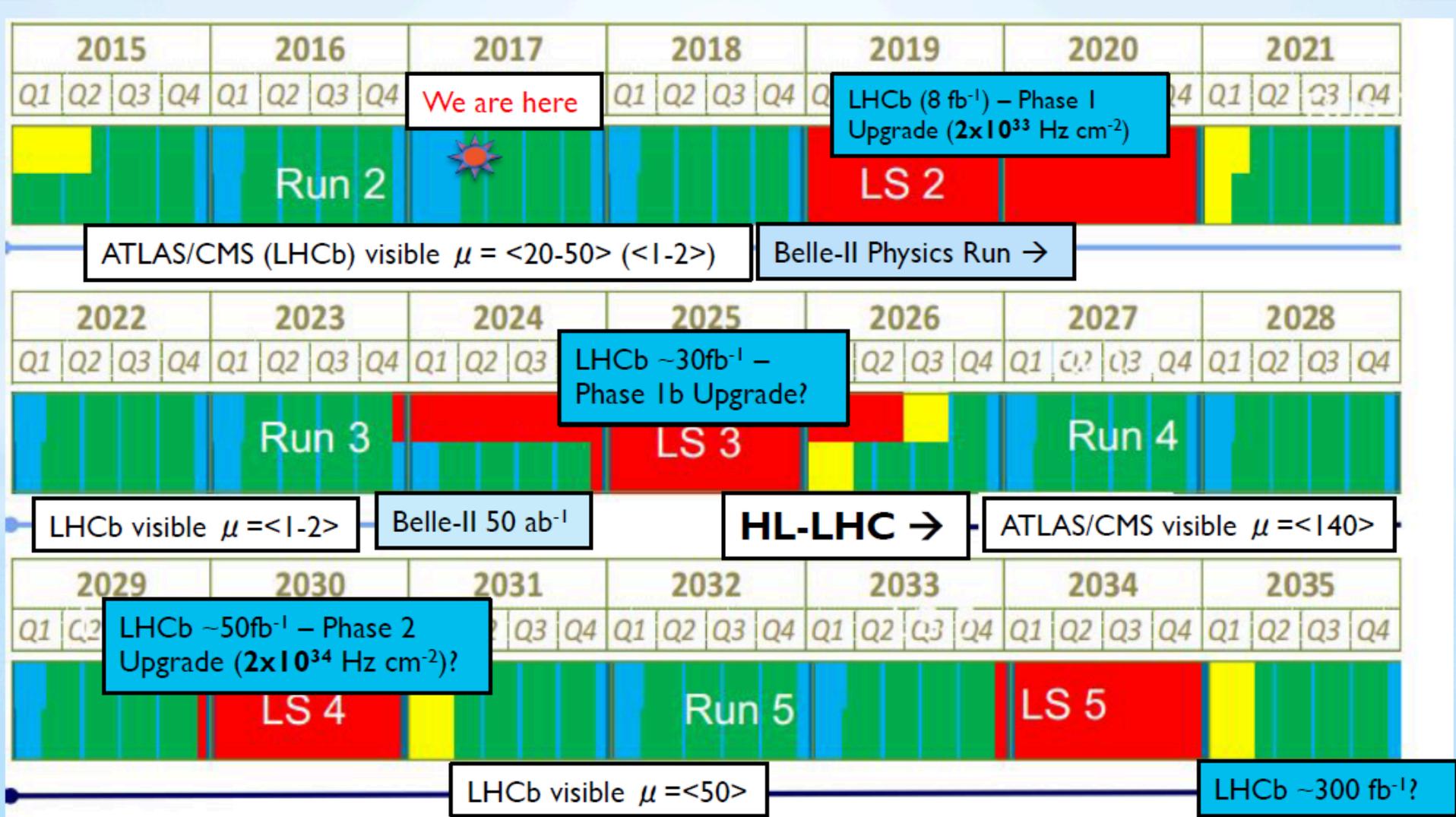
Rare decays at LHCb



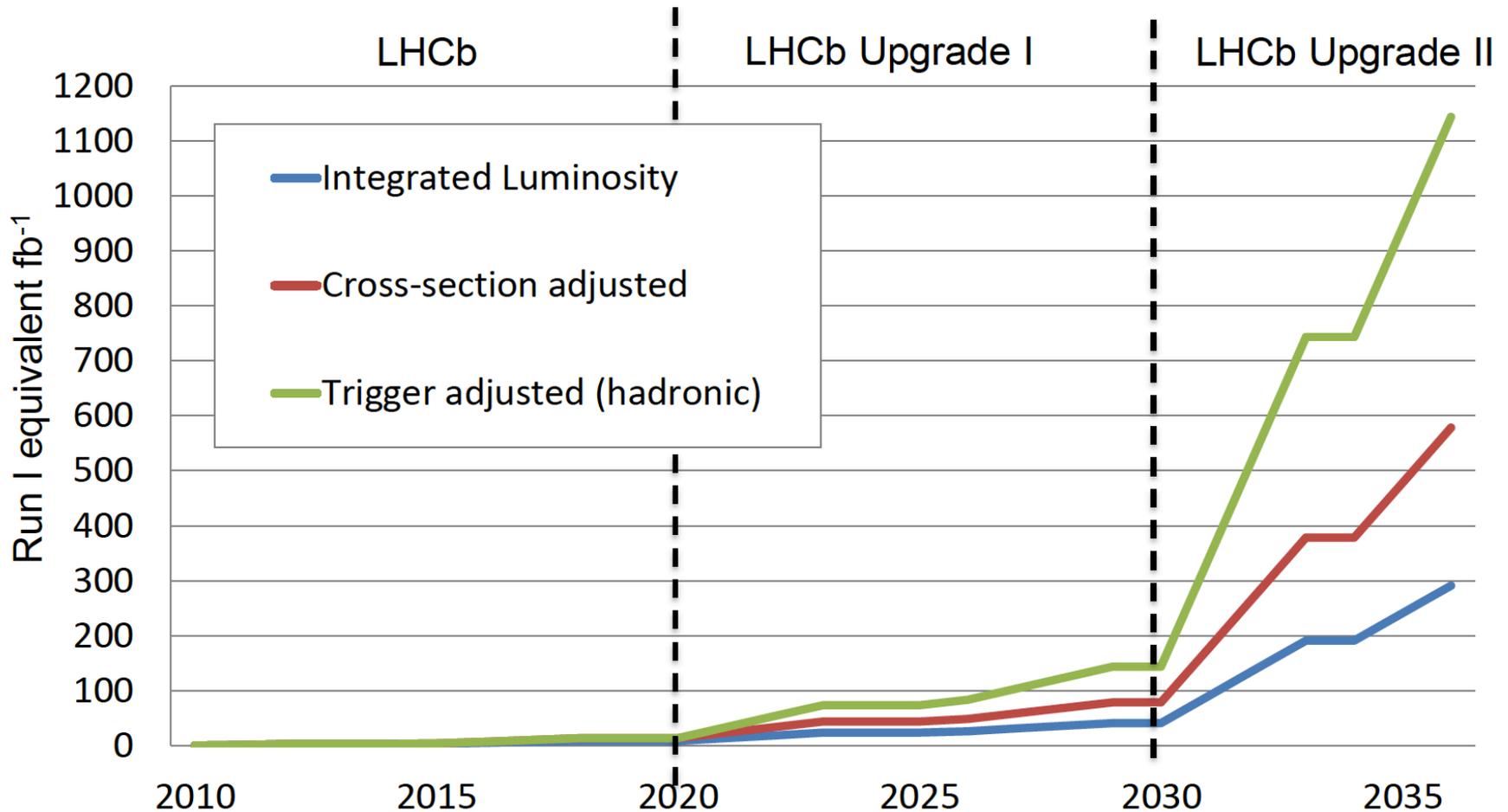
Jibo HE (UCAS)



The LHCb upgrades

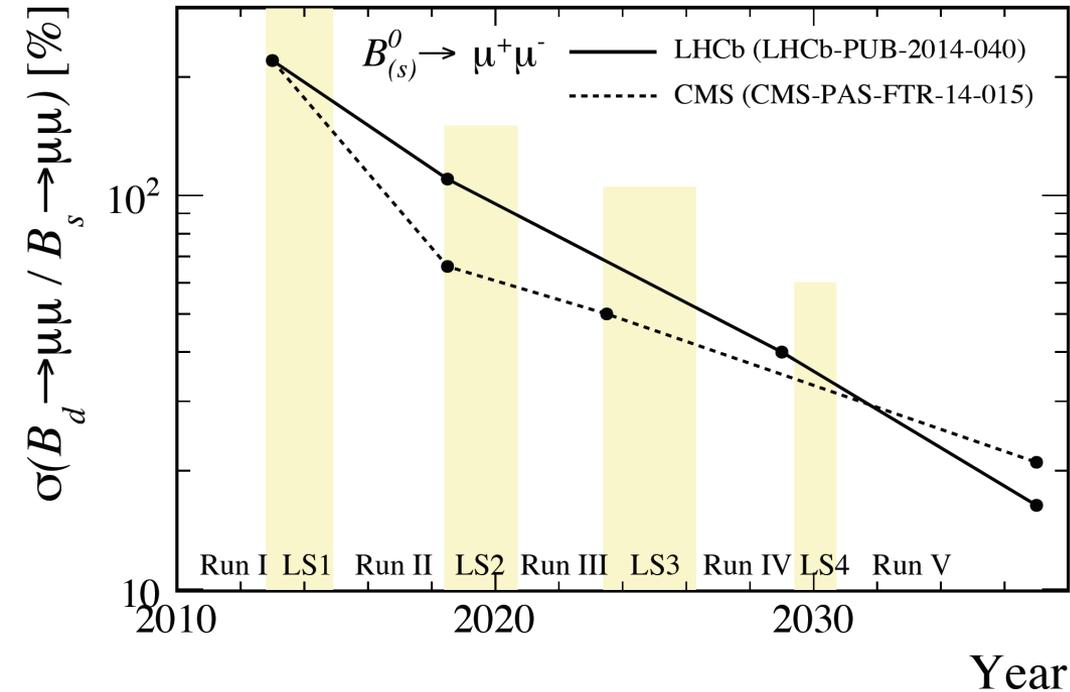


LHCb statistics-timeline

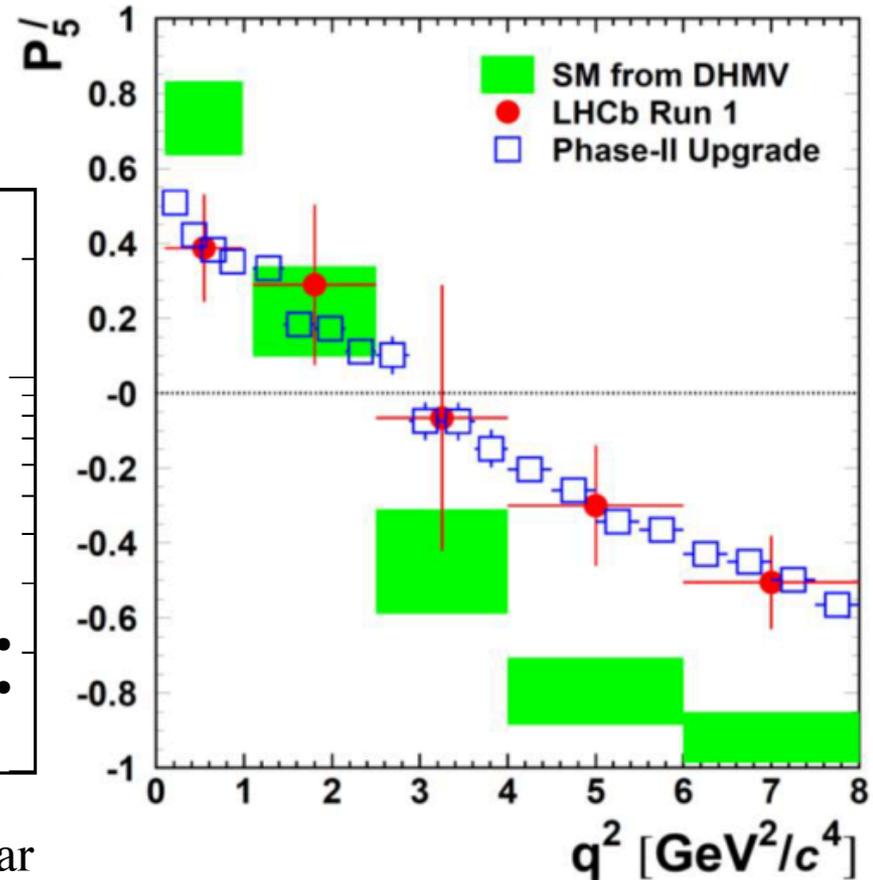


After the upgrade...

$$B_{(s)} \rightarrow \mu^+ \mu^-$$



$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$



Summary

- LHCb performed the world-leading measurements of rare decays:
 - Very rare decays, e.g., $B_{(s)} \rightarrow \mu^+ \mu^-$, $B_{(s)} \rightarrow \tau^+ \tau^-$
 - LFV, e.g., $B_{(s)} \rightarrow e^+ \mu^-$
 - Electroweak penguin, e.g., $B \rightarrow K^{(*)} \mu^+ \mu^-$
 - Radiative, e.g., $B_s \rightarrow \phi \gamma$
 - Rare Strange, e.g., $K_S \rightarrow \mu^+ \mu^-$
- Run-II data-taking ongoing well, upgrade(s) under its way, stay tuned!